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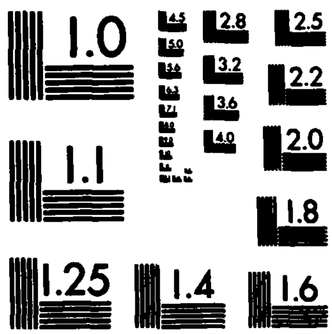

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COLLEGE OF ENGINEERING

THE INFLUENCE OF SURFACE ROUGHNESS
ON THE TRANSFER AND WEAR OF POLYMERS

FINAL REPORT

N. S. Eiss, Jr.

Professor of Mechanical Engineering

30 September 1983

U. S. Army Research Office

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Polymers, plastics, wear, abrasive wear, fatigue wear, surface topography, surface roughness, polyvinyl chloride, polyimide, polytetrafluorethylene, molecular weight, crystallinity.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Wear mechanisms of polymer sliding systems were studied. The wear rates of rigid polyvinyl chloride and low density polyethylene pins sliding on ground steel disks decreased as the average asperity curvature and the depth of penetration of the asperities in the polymer decreased. Observation of the sliding of polycarbonate and polyvinyl chloride disks against model asperities in the scanning electron microscope showed that elastic and plastic flow of the polymers around the asperities was much more evident than the formation

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20. ABSTRACT CONTINUED

of wear particles by fracture. A steel ball sliding on polycarbonate, polyvinyl chloride, polyethyleneterephthalate, and three polyimides required 20 to 550 cycles of sliding before wear particles started to form. A rise in friction preceeded the visualization of the wear particles. The fatigue wear of polyimide films on steel substrates in a ball on polymide test was lowest for the polyimide with the lowest T_g and lowest modulus. The wear of polytetrafluoroethylene was found to decrease as the molecular weight and crystallinity increased. The wear debris had lower molecular weight but slightly increased crystallinity.

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Problem Statement

The major objective of the proposed investigation was to determine the topographical features of hard surfaces which were most significant in the transfer and wear of polymers in multiple pass, high speed sliding. The investigation had the following phases:

1) the influence of the curvature of asperities on the wear of rigid polyvinyl chloride, PVC, and low density polyethylene LDPE.

2) observations of abrasive wear particles of polycarbonate, PC, and PVC in the scanning electron microscope, SEM.

3) fatigue wear and friction measurements of PC, PVC, ultra high molecular weight polyethylene, UHMWPE, polyethyleneterephthalate, PET, and three polyimides.

4) The effect of crystallinity and fine structure on the wear of polytetrafluoroethylene, PTFE, sliding on ground steel surface.

The major results of these four phases are summarized in the following sections.

Summary of Results

Phase I Influence of Asperity Curvature on Polymer Wear

The major purpose of this phase was to determine the effect of curvature of asperities on the wear of polymers. The unique feature of this study was that the curvatures of the steel asperities were changed by etching without significantly changing the arithmetic average roughness of the surface.

In general, the wear rates of PVC and LDPE decreased as the curvature of the asperities decreased. Since a decrease in stress resulting from a decrease in curvature is predicted by Hertzian elastic contact models, it can be inferred that the wear rate decreased as the stress in the polymer decreased. A second factor which affected the wear rate was the average depth of penetration of the asperities into the polymer. The average depth of penetration was calculated from surface profile data and the plastic deformation model for estimating the real area of contact. When the average depth of penetration was constant, the wear rate was proportional to the curvature of the asperities. However, when the average penetration depth varied, it was found that the wear rate decreased as both parameters decreased, a relationship that was illustrated with a three-axis graph as shown in Figure 1.

The wear-sliding distance curves exhibited a run-in period during which the wear rate was higher than the steady state wear rate. The wear rate of the steady state wear was calculated using a linear regression. When the regression line was extrapolated to zero sliding distance, the wear calculated at zero sliding distance was that caused by the higher wear rates during run-in. The run-in wear decreased with

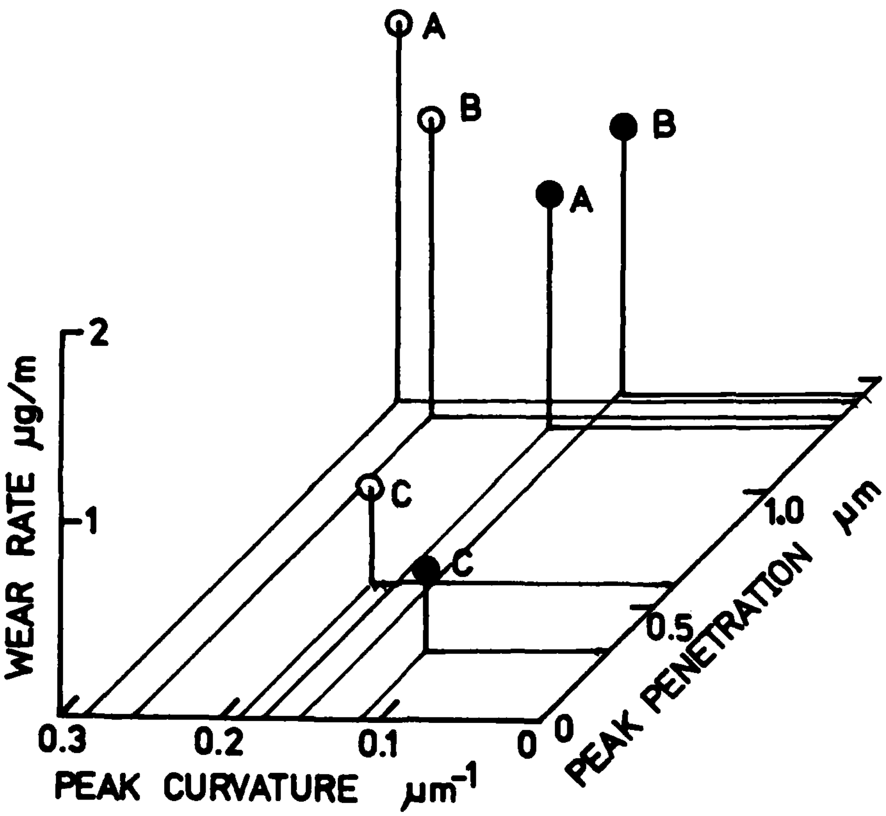

Fig. 1 Steady State Wear of PVC as a function of peak curvature and peak penetration.

asperity curvature and was insignificant at curvatures less than 0.1 μm^{-1} for PVC and LDPE. The run-in wear was primarily caused by the asperities abrading the polymer. The transferred polymer modified the asperity shape (primarily by a filling-in process) until a geometry was achieved that resulted in the steady state wear regime. It is believed that the steady state wear in these experiments was caused by a combination of the abrasive and fatigue wear mechanisms.

Phase 2 SEM Observations of Wear Particle Formation

The major purpose of this phase was to provide confirmation of the wear particle formation mechanism used in a model for abrasive wear of polymers.* In this model, it was assumed that a hard asperity penetrating a polymer would remove polymer wear particles only if the asperity slope exceeded a critical slope which was specific to each polymer. Since an asperity usually has slopes which range from zero at the peak to a maximum value, some of the polymer would flow around the asperity either elastically or elastically and plastically.

An apparatus was constructed in which a polymer disk could be rotated while a model asperity was spring loaded against the edge of the disk. The apparatus was placed in the SEM and the contact between the disk and the asperity was observed. The model asperities were produced by grinding a steel block with a coarse-grit wheel so that a rough topography (arithmetic average roughness greater than 5 μm) was produced, scratching a steel surface with a razor blade to produce two

* Eiss, N. S., "The Wear of Polymers by Transfer to Hard, Rough Surfaces," Final Report to USARO, Grant No.DAAG 29-77-G-0102, VPI&SU, Blacksburg, VA, February 1981, Appendix B.

elevated parallel asperities, and grinding a wedge with a slope of 20 degrees.

For all the model asperities, both elastic and plastic deformation of PC and PVC were observed as the polymer disks moved passed the steel asperity. In addition, polymer wear debris was extruded from the interface and also accumulated on the leading edge of the asperity. In some cases the accumulation was sufficient to force the disk and asperity apart. However, in no instance was the fracture process leading to a wear particle ever observed. If it occurred it was out of the field of view in the SEM.

These observations led the investigators to infer that elastic and plastic deformation are much more common than the propagation of cracks and wear particle formation in the initial stages of sliding. This inference lead to the conclusion that fatigue wear may be the predominant wear mechanism in polymer-metal sliding contacts.

Phase 3 Polymer Fatigue Wear Studies

The experiment used to study fatigue wear was a steel ball bearing sliding on a rotating polymer disk. The smoothness of the ball minimized abrasive wear and no significant transfer by adhesive wear was observed. The most important evidence which was consistent with a fatigue wear model was the number of cycles required for wear particles to be generated. This incubation period varied from 25 cycles for PC to 300 cycles for PVC for a 3.1 mm dia. ball, normal load of 10 N and a sliding speed of 4 cm/s. Wear particles were never observed for UHMWPE. The first observation of wear particles was preceeded by a rise in the coefficient of friction, from 0.15 to 0.30 for PVC and 0.33 to

0.50 for PC. The application of the following liquids: water, methanol, mineral oil, and water with three percent trisodium phosphate, all suppressed the wear particle formation and the preceeding rise in friction.

Similar fatigue tests were performed on 50 μm thick polyimide films cast on stainless steel substrates. In these tests the polyimides had three structures which differed only in one linking group within the monomer: -O-, $-CH_2-$, and -CO-. The purpose of these tests was to determine the influence of these different linking groups on the fatigue wear of the films. Two measures were used to characterize the fatigue wear, the number of cycles to initiate wear and the wear rate after wear initiated. The table below summarizes the results.

Wear Rates and Properties for Polyimides

Linking Group	Incubation Cycles	Wear Rate* (mm^2/kc)	Elastic Modulus (GPa)	Tg (^oC)
CH_2	269	1.71	11.94	295
O	557	0.56	9.74	257
CO	115	1.68	12.39	288

* Load-5N, Sliding Speed 0.63 m/s, wear volume is proportional to cross section area of wear track.

There is general agreement between the incubation cycles and wear rates, i.e. the greater the number of cycles to indicate wear, the lower the subsequent wear rate. The most flexible -O- linkage (indicated by the lowest Tg) caused the lowest wear rate. From this result it can be inferred that the flexibility of the polyimide chain permits chain rotation in response to applied stresses rather than chain scission.

There was no statistical difference in either the incubation cycles or the wear rates for the $-CH_2-$ and -CO- linkages.

The correlation of the wear rate with the elastic modulus is also consistent with the fatigue wear model which states that the wear rate is proportional to the modulus raised to a power 2t/3 where t is an empirically determined constant defined by the following equation:

$$N = (S_o/S)^t$$

where N is the number of cycles to failure

S_o is the stress required for failure in one cycle

S is the applied stress.

Typical values of t found in fatigue tests were 3.5 for LDPE and 9 for polymethyl methacrylate, PMMA*. Thus small changes in the elastic modulus can lead to large changes in the fatigue wear.

The polyimide with the -0- linkage also had lower friction than those with the $-CH_2-$ and -CO- linkages. In addition, the transiton in friction which preceeded the start of wear was longer for the -0- linkage than for the other linkages which had quite abrupt transitions.

A variation of the steel ball sliding on the polymer disk was used to determine whether or not the polymer exhibited a modulus change during incubation. Such a change was observed in constant-strain, bending fatigue tests of polymer+ In these experiments, the penetration of the ball into a PET disk was held constant and the normal and tangential loads were monitored during sliding. During the incubation

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* Lancaster, J. K. "Basic Mechanisms of Friction and Wear of Polymer," Plastics and Polymers, Vol. 41, Dec 1873, p. 297-305.

\+ Rabinowicz, S. and R. Beardmore, "Cyclic Deformation and Fracture of Polymers," Jl. Mat. Sci., Vol. 9, No. 1, 1974, pp. 81-99.

period there was no significant decrease in the normal load, which indicated that there was no significant change in the elastic modulus. During the incubation period, it was found that the mean value of the coefficient of friction increased while its variation (standard deviation) decreased.

Summary of Phases 1, 2, and 3

The evidence accumulated in this research supports the fatigue mechanism of polymer wear as a major mechanism in the steady state wear process. The most incontrovertible evidence is the incubation period of sliding before wear particles begin to form in an experiment where abrasive and adhesive wear mechanisms are not significant. In multiple pass sliding experiments of polymer pins on rough metal disks, the initial roughness of the metal disk is a major factor in determining which wear mechanisms dominate during sliding.

If a run-in period is observed in which the wear rate is significantly higher than the steady state wear, the wear is predominantly abrasive wear. The abrasively removed polymer adheres or mechanically attaches to the metal asperities modifying the asperity curvature and reduces stress levels on the contacting polymer. During steady state wear, a combination of abrasive and fatigue wear mechanisms contribute to the wear process.

If no significant run-in period occurs and steady state wear exists from the start of the experiment, then the metal topography is such that no significant modification of the asperity topography occurs by transfer. The wear particles are generated by the combination of abrasive and fatigue mechanisms.

In some cases, the onset of wear is delayed or the initial wear occurs at a rate which is smaller than the steady state wear rate. In this case, the topography of the metal surface is so smooth that the abrasive wear component is quite small. The transition to the higher steady state wear occurs when the fatigue mechanism became dominant.

It is recognized that a spectrum of wear behaviors can be observed depending on operating conditions (load, speed, environment), test geometry, and materials. Thus, no one model of the wear process will suffice for all cases. However, evidence to date indicates tha the fundamental mechanisms of wear, i.e. adhesive transfer, abrasive wear, fatigue wear, and, in extremely severe conditions, melting or degradation can be combined to explain the majority of the observations.

Phase 4 Friction and Wear Studies of PTFE

During two years of this research, Ms. Ting-yung Hu was a visiting scholar at VPI&SU. Her research on the effect of crystallinity, molecular weight, and fine structure on the wear of PTFE was substantially aided by the use of our surface topography analysis system to characterize steel disks on which pins of PTFE were rubbed. By carefully controlling the steel roughness, the experimental scatter in wear results was reduced so that the small differences in wear rate caused by different molecular weights and crystallinities could be detected.

Several PTFE moldings were prepared from various types of resin powder by different procedures including compression molding and extrusion molding, followed by different treatments including quenching, annealing, and slow cooling. In these moldings, the number-average molecular weight ranged from 1.7×10^6 to 17.3×10^6 and crystallinity ranged from 25% to 64% as determined by Differential Scanning Calorimetry (DSC). The particulate and banded fine structures, with a striation length range from 0.1 to 0.4 μm were found. An increase in crystallinity caused by slow cooling or annealing was accompanied by an increase in dimensions of fine structure.

A wear study was carried out in a pin-on-disk apparatus in a temperature range from 30 to 35°C. It was found that an increase in molecular weight or crystallinity produced a decrease in wear rate. A study of wear debris revealed that its molecular weight was 1-2 orders of magnitude lower and its crystallinity was 1-8% higher than those of bulk samples. The above results were explained in terms of a wear mechanism in which both crystalline and amorphous domains were pulled out from the bulk accompanied by fracture and/or slippage of molecular chains.

Lists of Publications and Theses

Papers in Journals and Proceedings

Hu, T. Y., and N. S. Eiss, Jr., "The Effects of Molecular Weight and Crystallinity on Wear of Polytetrafluoroethylene," Wear of Materials 1983, ed. by Ludema, K. C., ASME, 1983, pp. 636-642.

Hu, T. Y., and N. S. Eiss, Jr., "The Effects of Molecular Weight and Cooling Rate on Fine Structure, Stress-Strain Behavior and Wear of PTFE," Wear, Vol. 84, No. 2, 1983, pp. 203-215.

Eiss, N. S., Jr., and S. C. Milloy, "The Effect of Asperity Curvature on Polymer Wear," Wear of Materials 1983, ed. by Ludema, K. C., ASME, 1983, pp. 650-656.

Master of Science Theses

Milloy, S. C., "The Effect of Surface Topography on Polymer Wear," Master of Science Thesis, VPI&SU, Blacksburg, Va., October 1981.

Carter, J. T., "An Investigation of Polymer Wear Due to Fatigue Using a Constant Strain Wear Test," Master of Science Thesis, VPI&SU, Blacksburg, Va., February 1983.

Jones, J. W., "The Correlation of Chemical Structure to Tribological Properties of Polyimide Thin Films," Master of Science Thesis, VPI&SU, Blacksburg, Va., May 1983.

Potter, J. R., "An Investigation of Friction and Wear Mechanisms in Selected Thermoplastics," Master of Science Thesis, VPI&SU, Blacksburg, Va., August 1983.

Participating Scientific Personnel and Degrees Granted

Dr. Norman S. Eiss, Jr., Professor of Mechanical Engineering, Principal Investigator

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Ms. Ting-yung Hu, Visiting Scholar, Mechanical Engineering

Joseph R. Potter, Graduate Research Assistant, Master of Science degree in August 1983

Sean C. Milloy, Graduate Research Assistant, Master of Science degree in October 1981

J. Thomas Carter, Graduate Research Assistant, Master of Science degree in February 1983

J. W. Jones, Graduate Research Assistant, Master of Science degree in May 1983

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